

Soil properties and productivity as affected by topsoil movement within an eroded landform[☆]

S.K. Papiernik^{a,*}, T.E. Schumacher^b, D.A. Lobb^c, M.J. Lindstrom^a, M.L. Lieser^d,
A. Eynard^b, J.A. Schumacher^b

^a USDA-Agricultural Research Service, North Central Soil Conservation Research Laboratory, 803 Iowa Avenue, Morris, MN 56267, USA

^b South Dakota State University, Department of Plant Sciences, 247A SNP, Brookings, SD 57007-2141, USA

^c University of Manitoba, Department of Soil Science, 276 Ellis Building, Winnipeg, Man., Canada R3T2N2

^d USDA-Natural Resources Conservation Service, 1004 Frontier Drive, Fergus Falls, MN 56537, USA

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ABSTRACT

In hilly landforms subject to long-term cultivation, erosion has denuded upper slope positions of topsoil and accumulated topsoil in lower slope positions. One approach to remediate these eroded landforms is moving soil from areas of topsoil accumulation to areas of topsoil depletion, termed here soil-landscape rehabilitation. These experiments were conducted in an eroded undulating landform typical of the prairie pothole region. The summit, shoulder, upper and lower backslope were depleted in soil nutrients and organic carbon and had enriched inorganic carbon contents through the incorporation of calcareous subsoil material into the tilled layer. Surface soil organic carbon contents in lower slope positions were at least twice that in the most eroded positions. Six replicate plots were established that extended from the summit to the toeslope of the test area. Soil-landscape rehabilitation was performed on three plots by moving 15–20 cm of soil from the lower slope (footslope and toeslope) to the upper slope (summit, shoulder, and upper backslope) positions. The three remaining plots were undisturbed. In lower slope positions, soil properties were shifted upwards with respect to the soil surface by 15–20 cm in rehabilitated plots (where soil was removed). In upper slope positions, soil properties were shifted downwards by 15–20 cm in rehabilitated plots (where soil was applied, original soil was buried). After rehabilitation, the top 15 cm of soil in rehabilitated plots had characteristics similar to the footslope and toeslope, from which the soil was taken. Thus, soil properties were much more uniform from summit to toeslope in rehabilitated plots compared to undisturbed plots. Productivity was measured in two cropping years characterized by summer drought conditions. In rehabilitated plots, yields were relatively consistent across landscape positions, whereas in undisturbed plots, yields were depressed in eroded landscape positions. Grain yields in rehabilitated plots were increased by 30% in areas of soil addition. These yield increases were accompanied by yield decreases of 50% (year 1) and 20% (year 2) in areas of soil removal. Results indicate that movement of accumulated topsoil from lower slope positions to eroded upper slope positions can result in large yield increases in upper slope positions and more consistency in crop yields across the landscape, but additional research is needed to provide a more complete analysis of the soil productivity impacts of this approach.

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1. Introduction

Erosion affects properties of soil profiles that can impact agricultural productivity. Tillage erosion, the progressive downslope movement of soil through the mechanical action of tillage implements, is being increasingly recognized as a major erosive force in hilly areas. Different patterns of soil redistribution occur during water and tillage erosion. Tillage erosion results in the removal of soil from convex landscape positions, and soil loss by tillage erosion is usually greatest in crest/summit, shoulder, and

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* Corresponding author. Tel.: +1 320 589 3411; fax: +1 320 589 3787.

E-mail address: Sharon.Papiernik@ars.usda.gov (S.K. Papiernik).

upper backslope positions. Slope gradient and slope curvature are important determinants of tillage erosion rates (Lobb et al., 1999). Soil movement by water erosion increases with increasing slope gradient and length, and the rate of soil loss by water erosion is usually greatest in the middle to lower backslope. Both tillage erosion and water erosion can result in soil accumulation in concave landscape positions. Tillage and water erosion interact to result in complex redistributions of soil and soil constituents within a landform (Li et al., 2007).

Studies of erosion-induced changes in soil properties at the field scale have consistently shown that surface soil organic carbon, nitrogen, and phosphorus concentrations are higher in areas of soil accumulation compared to areas of soil removal by erosion (Gregorich and Anderson, 1985; Heckrath et al., 2005; Papiernik et al., 2005, 2007; Pennock et al., 1994). Surface soil pH is high in eroded landscape positions in soils formed from calcareous parent materials (Battison et al., 1987; Papiernik et al., 2005, 2007; Pennock et al., 1994). Soil concentrations of nutrients and organic matter are higher throughout the upper profile in uncultivated landscapes than in eroded cultivated landscapes at the same landscape position (Gregorich and Anderson, 1985; Malo et al., 2005; Papiernik et al., 2007). Surface soil organic matter and nutrient contents tend to decrease with increasing erosion phase in cultivated soils (Arriaga and Lowery, 2005; Battison et al., 1987; Fenton et al., 2005); erosion also affects soil physical properties such as soil texture and saturated hydraulic conductivity (Battison et al., 1987; Lowery et al., 1995).

Topsoil removal by tillage and water erosion decreases agricultural productivity (Battison et al., 1987; Heckrath et al., 2005; Kosmas et al., 2001; Olson and Carner, 1990; Papiernik et al., 2005; Tsara et al., 2001). Several studies have investigated soil properties and crop yields in areas from which topsoil was removed to simulate soil erosion. Where topsoil was removed, addition of topsoil is more effective in increasing grain yields than addition of fertilizer (Larney et al., 2000; Massee, 1990; Massee and Waggoner, 1985; Mielke and Schepers, 1986). Deleterious effects of topsoil removal (including reduced organic matter and nutrient content, increased bulk density, and lower available soil water) were shown to persist 20 years after soil movement (Lindstrom et al., 1986).

Replacement of topsoil has been proposed as an approach to improve soil quality for crop growth in areas from which topsoil has been removed for construction or by erosion (Massee, 1990; Mielke and Schepers, 1986; Verity and Anderson, 1990; Grote and Al-Kaisi, 2007). This experiment was established as a replicated study to evaluate soil properties as a function of landscape position in a landform strongly affected by tillage erosion, and to determine the impact of intra-landform topsoil movement on soil productivity and the properties of soil profiles at this eroded site.

2. Methods

2.1. Site

Experiments were conducted in a 0.8-ha portion of a 28-ha (70 ac) field near Morris in west central Minnesota (45.65°N, 95.83°W), an area characterized by undulating topography with slopes generally <10%. The site consists of a ridge and a surface-drained wetland (Fig. 1). This field has been cultivated for approximately 100 years, with annual moldboard plowing for much of its history; it has been cropped predominantly to wheat (*Triticum aestivum*), soybean (*Glycine max*), and corn (*Zea mays*). For the 10 years prior to this study, tillage consisted of fall chisel plowing following corn and spring tillage following wheat and soybean.

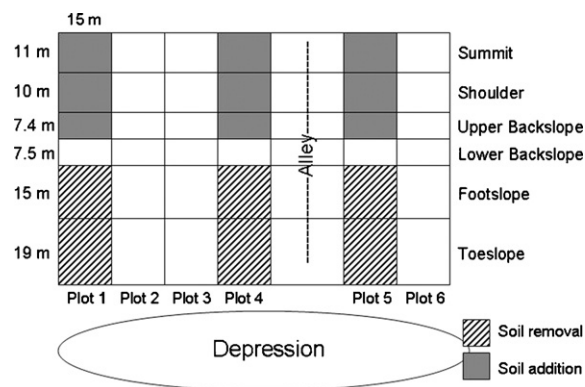


Fig. 1. Schematic diagram of experimental site, including locations and approximate dimensions of plots and subplots (landscape positions).

A preliminary soil survey was completed in October, 2005 to characterize the site for additional sampling for soil property determination. Soil morphology was determined in the field according to standard methods (Schoeneberger et al., 2002). Based on this survey, the field site was separated into six plots, each 15 m wide and extending from the summit to the toeslope. Visual assessments of slope gradient were used to segment each plot into six landscape positions, which are designated as subplots: summit, shoulder, upper backslope, lower backslope, footslope, and toeslope (Fig. 1). Subplots ranged from 7.4 m (upper backslope) to 19 m (toeslope) in the up/downslope direction (Fig. 1). The alley has a slight cross-slope, and no plots were established in this area of slope complexity.

Pre-rehabilitation soil sampling was completed in October 2005, following wheat harvest. Soil cores (5-cm diameter) were collected to a depth of 0.9–1.2 m in each subplot. Horizonation was determined by a pedologist using standard methods (Schoeneberger et al., 2002), and cores were sectioned by horizon. Additional soil samples (3-cm diameter) were collected at the subplot corners (Fig. 1) and sectioned into depth increments 0–10 cm, 10–25 cm, and 25–40 cm. Each sampling point was located (latitude, longitude, and elevation) using a Trimble AgGPS-132 with differential corrections (Omnistar).

2.2. Erosion estimates

To develop tillage and water erosion estimates, a digital elevation model of the study site and the surrounding area was developed using a Leica survey grade DGPS system, with points located on a 3-m grid. Erosion by tillage, water, and the combined effects of tillage and water was estimated at each node on the grid using the Water and Tillage Erosion Model (WATEM, Van Oost et al., 2000) using the approach described in Schumacher et al. (2005). Water erosion model parameters were: a rainfall-runoff erosivity factor (R) of 90, a soil erodibility factor (K) of 0.28, a cover/management factor (C) of 0.21, and a support practice factor (P) of 1. The tillage transport coefficient was 718 kg m^{-1} , which is typical of the intensive tillage dominating the site's history.

2.3. Soil-landscape rehabilitation

Soil movement for soil-landscape rehabilitation was done on 9 November 2005 when soil moisture and other conditions were judged suitable. A John Deere 760A scraper with a capacity of 9 m^3 was used for soil movement, with scraper traffic in the up/down slope direction. On each pass traveling upslope, <10 cm of soil were removed from the toeslope and footslope (filling the scraper to 30–40% capacity) and deposited evenly across the upper

backslope, shoulder, and summit, skipping over the lower back-slope. Turning and downslope traffic was out of the plots. The scraper made multiple upslope passes in each rehabilitated plot. Undisturbed plots had no scraper traffic. In each plot, the size of the area of soil removal ($533 \pm 14 \text{ m}^2$) was similar to the area of soil addition ($430 \pm 11 \text{ m}^2$), so the depth of soil removal from the toeslope + footslope was nearly equal to the depth of soil addition to the upper backslope + shoulder + summit: 15–20 cm. Immediately following soil movement, areas of soil removal and addition were tilled in the up/down slope direction, then the entire site was tilled along the contour using a chisel plow with straight shanks set approximately 20–25 cm deep.

Post-rehabilitation soil sampling was completed in May 2006 prior to spring tillage and planting. Four soil cores (2-cm diameter) were collected throughout each subplot in two 30-cm segments and sectioned into depth increments of 0–15, 15–30, 30–45, and 45–60 cm. Samples from each depth were consolidated.

2.4. Determination of soil properties

Soil properties were determined by horizon (1-m deep pre-rehabilitation cores) or by depth (in pre- and post-rehabilitation cores) in air-dried, homogenized, sieved ($<2 \text{ mm}$) samples. Total carbon was determined by combustion using a LECO analyzer. Inorganic carbon (IC) was determined from the pressure increase resulting from CO_2 liberation upon addition of acid (Wagner et al., 1998). Soil organic carbon (OC) was calculated as the difference between total carbon and inorganic carbon. Soil pH was measured in a 1:1 slurry of 5 g of dry soil in 0.01 M aqueous CaCl_2 solution (Thomas, 1996). Total nitrogen content was determined by Dumas combustion and measured using a LECO 2000 CN analyzer (LECO Corporation, 2003). Measurements of Olsen-extractable phosphorus (Olsen and Sommers, 1982), ammonium acetate-extractable potassium (Knudsen et al., 1982), nitrate-N and ammonium-N (Mulvaney, 1996) were determined using standard soil test procedures. Electrical conductivity (EC) was determined in a 1:2 soil:solution slurry (Rhoades, 1996).

Soil bulk density was determined in October 2005 (prior to soil-landscape rehabilitation) and in October 2006 (following rehabilitation). Bulk density was determined in one location in each subplot at depths of 5–10 cm and 20–25 cm. Soil was excavated to the depth of interest, a 50 mm (diameter) \times 50 mm (length) brass cylinder was driven into the soil, the ends were squared off, and the cylinders were capped for transport to the laboratory. Samples were dried at 105°C and the mass of dry soil per known volume was determined. Gravimetric soil moisture was determined after rehabilitation in May 2006 (during crop emergence) in two cores per subplot in depth increments of 0–15, 15–30, 30–61, and 61–91 cm. Soil strength measurements were conducted following soil moisture determinations. Soil strength was measured by the resistance to penetration using a Bush recording penetrometer with a 30° angle cone tip with a maximum diameter of 13 mm. Three soil strength profile measurements were taken to a depth of 52 cm in each subplot.

To allow comparisons of soil properties between soil profiles, soil properties determined by horizon were converted to a depth basis. Pre-rehabilitation soil properties were determined in specific depth increments (0–10, 10–25, and 25–40 cm) at the subplot corners and by horizon in one deep core collected in approximately the center of each subplot. To compute pre-rehabilitation soil properties in each subplot, values determined by horizon were normalized to the depth increments 0–10, 10–25, and 25–40 cm: the value determined for each horizon was weighted (based on depth) by the fraction of the total that it contributed to the assigned depth increment. Subplot pre-

rehabilitation soil properties were determined by weighting each of the subplot corner samples by a factor of 0.125 and the deep core by a factor of 0.5. A similar normalizing approach was used to compare pre- and post-rehabilitation soil properties, in which all data were converted to depth increments 0–15, 15–30, 30–45, 45–60, and 60–120 cm.

2.5. Soil productivity

The site was planted to glyphosate-resistant soybean in the first season after soil movement. Seeds were planted in 38-cm rows running approximately on the contour. No fertilizer was applied to the soybean crop. Subplots were harvested using a plot combine with a 1.5-m head. In each subplot, two sections were harvested, comprising eight rows per plot. The harvested area was measured for each subplot. Yield was determined by weight (kg ha^{-1}) at 13% moisture.

The site was planted to glyphosate-resistant corn in the second season after soil movement. Fertilization included fall-applied nitrogen (0.13 Mg ha^{-1} as anhydrous ammonia) and spring-applied N, P, and K (0.24 Mg ha^{-1} of 27–70–40). Four rows in each subplot were harvested using a plot combine, and the harvested area was measured. Yield was determined by weight (kg ha^{-1}) at 15.5% moisture.

3. Results and discussion

3.1. Erosion estimates

Soil flux via tillage, water, and their integration was determined at 5-m spacing, based on the digital elevation model and WATEM (Fig. 2). Soil loss by tillage erosion occurred throughout the upper slope, with the greatest loss predicted in the shoulder slope. Soil translocation by tillage resulted in net soil accumulation in the footslope and toeslope. The lower backslope was an area of little net soil movement by tillage under the conditions stipulated by the model: the amount of soil brought into this landscape position was about the same as the amount of soil leaving this landscape position. Soil loss by water erosion occurred throughout most of the landform, with net deposition occurring only in the toeslope. This landform extends beyond the studied toeslope to a depression (Fig. 2), and the greatest rate of soil accumulation by water erosion was predicted in the depression (Fig. 2). Soil loss by water erosion was greatest in the backslope, and only slight soil loss occurred near the summit. The model integrating tillage and water erosion predicted very high soil loss in the shoulder and upper backslope and net soil deposition in the footslope and toeslope (Fig. 2). Soil flux through tillage + water erosion ranged from a net soil loss of $130 \text{ Mg ha}^{-1} \text{ year}^{-1}$ to a net soil gain of $>100 \text{ Mg ha}^{-1} \text{ year}^{-1}$. These erosion values represent intensive tillage (moldboard plowing plus secondary tillage), which was used for most of the site's 100-year cultivated history.

3.2. Pre-rehabilitation soil properties

3.2.1. Soil series

The preliminary soil survey indicated that six soil series (Lewis et al., 1971; Soil Survey Staff, 2008) were represented in this landform (Table 1). Soils were formed in calcareous till. Upper slope positions (convex) were eroded and characterized as belonging to the Buse series. At the summit, an Ap2 horizon provided evidence of historical deeper tillage, with the two Ap horizons being distinguished by color (Ap1 at 0–20 cm, Ap2 at 20–30 cm depth). Subsoil consisted of a Bk horizon extending from 30 to 58 cm, and a B horizon extending to 120 cm. This B horizon was

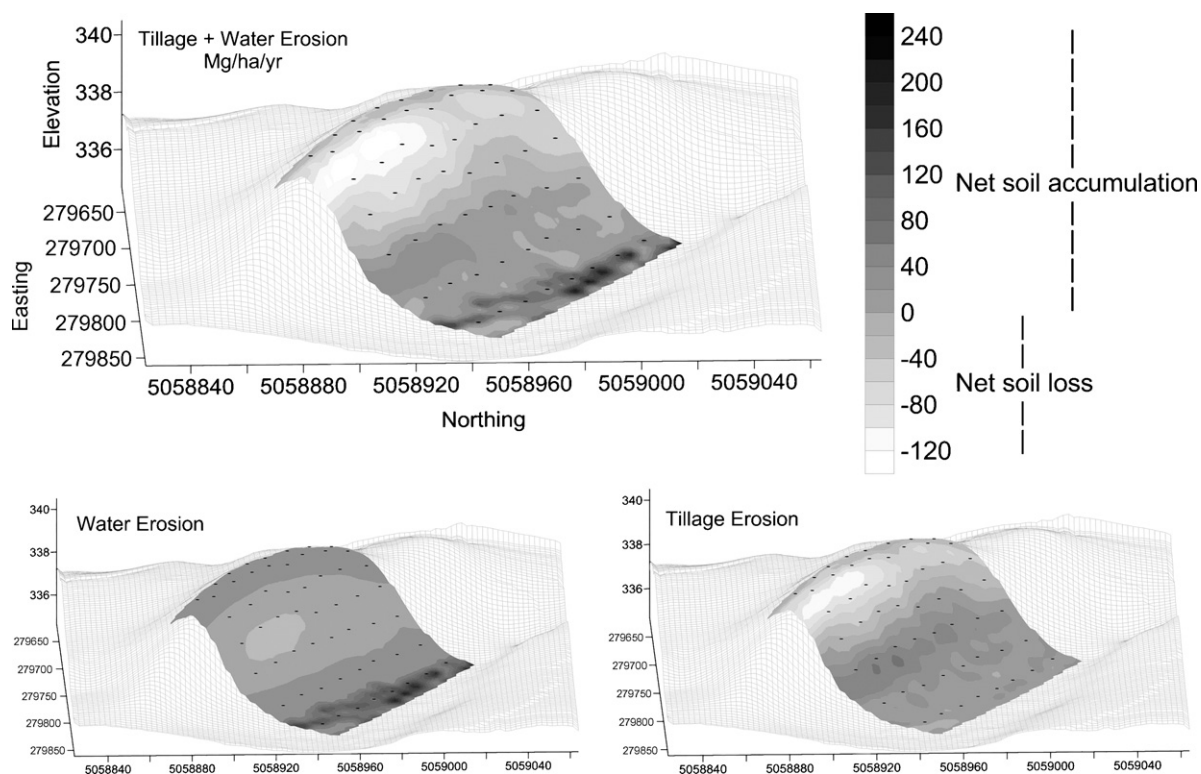


Fig. 2. Erosion estimates for the experimental site.

so classified because it was more highly structured than a C and had lower effervescence than a Bk. In the shoulder positions, the Ap horizon was shallow (13–20 cm) and strongly or violently effervescent. Subsoil consisted of two Bk horizons extending to depths of 70–90 cm with lime dispersed throughout the Bk horizon. It is likely that the soil in these landscape positions were similar to a Barnes loam prior to cultivation, but tillage and water erosion have truncated these profiles and removed the cambic horizons or incorporated the Bw horizon into the tilled layer.

The middle backslope soil was characterized as belonging to the Langhei series. The Ap horizon of this soil was non-mollic, and was strongly effervescent. A Bk horizon extended from the Ap (13 cm) to a shallow C (60 cm). Soil in the lower backslope was classified as a Hamerly with deposition. In this soil core, a strongly effervescent Ap horizon lay atop a non-effervescent A1 (23–53 cm deep), a strongly effervescent A2 (53–68 cm deep) and Bk horizons extending to 120 cm. The deposition of calcareous soil on top of non-calcareous soil in the backslope is a pattern typical of tillage erosion, in which soil from upper slope positions is translocated downslope (de Alba et al., 2004).

The lower slope positions (concave) are characterized as Marysland in the footslope, similar to an Oldham, but loamy in the toeslope, and Parnell in the depression. In these landscape positions, deposited soil of thickness ≥ 46 cm was observed in each core, and A-horizon material extended to >68 cm depth. The surface soil in the footslope and toeslope was strongly effervescent, which is a pattern typical of redistribution of soil by tillage within a landform, in which high-carbonate material from upper slope positions is mixed with low-carbonate material in the tilled layer of lower slope positions (de Alba et al., 2004). Macroinvertebrate shells in the A1 and A2 horizons in the depression (depths >58 cm) indicate that this wetland has experienced substantial influx of soil since it was drained.

3.2.2. Surface soil properties

Surface soil OC (Fig. 3) and other soil properties (data not shown) were uniform across the slope (at each landscape position) prior to soil movement. There were no significant differences in any measured soil property in rehabilitated versus undisturbed plots prior to soil movement.

Table 1
Soil series represented in the study landform prior to soil movement

Soil series	Landscape position	Description	Profile characteristics
Buse	Summit, Shoulder	Fine-loamy, mixed, superactive, frigid Typic Calciudolls	Removal of mollic and cambic horizons from original Barnes
Langhei	Middle Backslope	Fine-loamy, mixed, superactive, frigid Typic Eutrudepts	Non-mollic, strongly effervescent Ap
Hamerly	Lower Backslope	Fine-loamy, mixed, superactive, frigid Aeris Calciaquolls	Ap is depositional and strongly effervescent; overlies non-effervescent A
Marysland	Footslope	Fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Typic Calciaquolls	46 cm of depositional material overlies original A
Oldham-like (fine loamy)	Toeslope	Fine, smectitic, calcareous, frigid Cumulic Vertic Endoaquolls	46 cm of depositional material overlies original A
Parnell	Depression	Fine, smectitic, frigid Vertic Argiaquolls	Invertebrate shells present at depths >58 cm; shallower soils are depositional

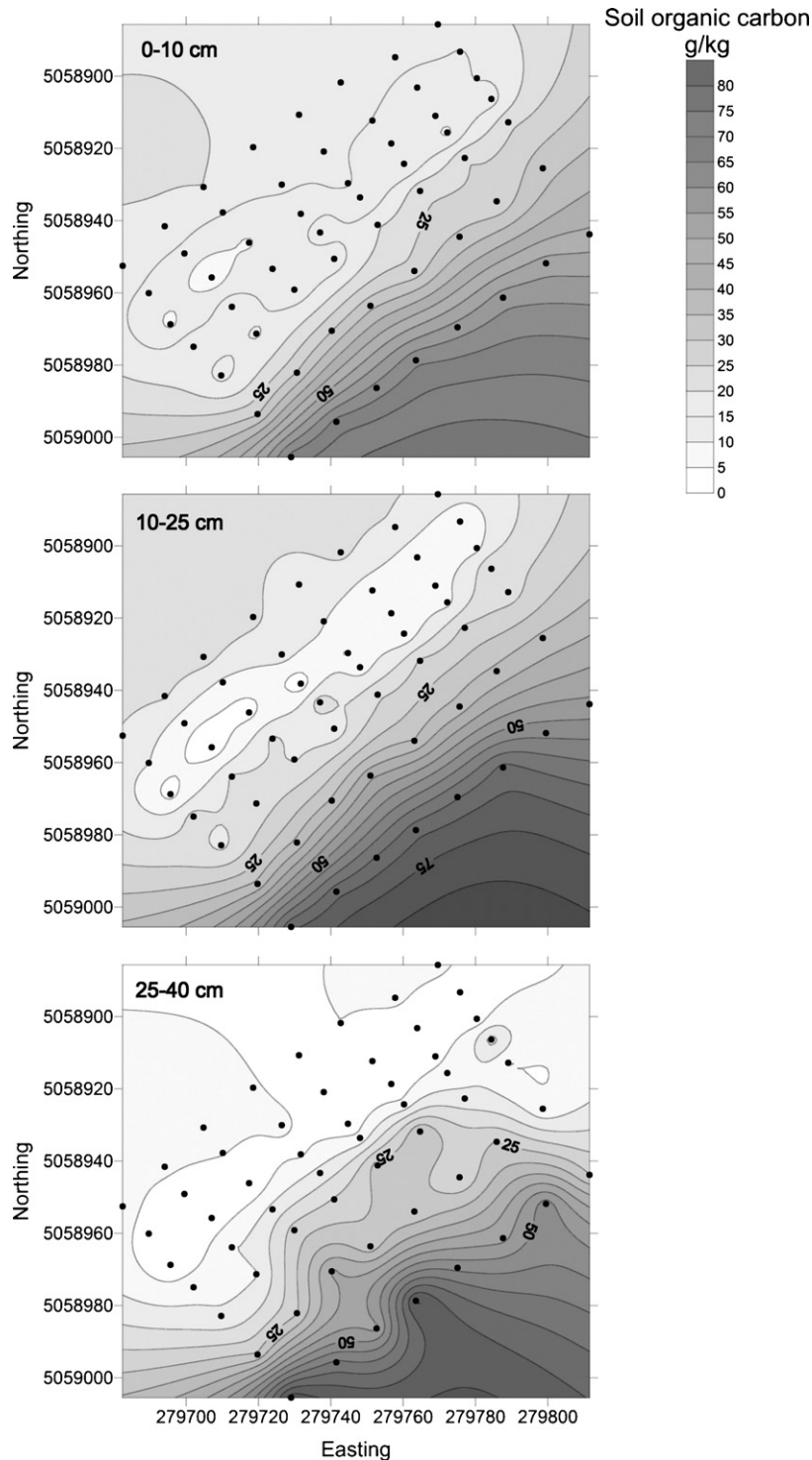


Fig. 3. Soil organic carbon content as a function of depth prior to soil movement for soil-landscape rehabilitation.

Landscape position had a strong influence on surface soil properties, with the toeslope having significantly higher surface soil total N, nitrate-N, Olsen P, OC, and EC than any other landscape position (Table 2). Nutrient and OC contents in the footslope were lower than in the toeslope, but generally significantly greater than in the upper landscape positions (Table 2). As is commonly observed in eroded landscapes (Verity and Anderson, 1990; Papiernik et al., 2005), the summit, shoulder, upper and lower backslope were depleted in soil nutrients and OC and had elevated IC contents (Table 2) due to the incorporation of subsoil (Bk)

material into the tilled layer. Surface soil in the toeslope had total N, P, and OC contents that were three to four times that in the upper backslope (Table 2). These topographic trends in soil properties are consistent with previous reports for organic matter and nutrients (Cox et al., 2003; Kravchenko and Bullock, 2000).

3.2.3. Soil properties with depth

Soil concentrations of nitrate-N, total N, P, K, OC, and EC significantly decreased with increasing depth in the upper profile (0–40 cm) in landscape positions of high soil loss by erosion

Table 2

Surface soil (0–10 cm depth) properties before soil movement for soil-landscape rehabilitation calculated from results for samples collected at each of the plot corners and the center of the plot

Soil property	Summit	Shoulder	Upper backslope	Lower backslope	Footslope	Toeslope
Organic carbon (g kg^{-1})	15.3 ± 0.5 c	11 ± 1 c	11 ± 2 c	14 ± 2 c	22 ± 1 b	41.1 ± 0.8 a
Inorganic carbon (g kg^{-1})	12 ± 1 ab	20 ± 2 a	22 ± 3 a	17 ± 4 ab	13 ± 3 ab	8.1 ± 0.7 b
pH	7.70 ± 0.02 a	7.73 ± 0.04 a	7.74 ± 0.03 a	7.69 ± 0.03 a	7.65 ± 0.01 a	7.67 ± 0.01 a
Electrical conductivity ($\mu\text{S cm}^{-1}$)	230 ± 5 bc	227 ± 4 bc	219 ± 5 c	232 ± 8 bc	265 ± 9 b	480 ± 20 a
Total N (g kg^{-1})	1.4 ± 0.0 c	1.1 ± 0.1 c	1.0 ± 0.1 c	1.4 ± 0.2 c	2.0 ± 0.1 b	3.8 ± 0.1 a
Nitrate-N (mg kg^{-1})	8.6 ± 0.1 c	8.5 ± 0.5 c	7.5 ± 0.6 c	10 ± 2 bc	14.3 ± 0.8 b	25 ± 1 a
Ammonium-N (mg kg^{-1})	3.9 ± 0.2 b	4.0 ± 0.2 b	4.0 ± 0.2 b	3.5 ± 0.3 b	4.5 ± 0.5 ab	5.6 ± 0.3 a
Olsen P (mg kg^{-1})	9.9 ± 0.7 bc	9 ± 1 bc	7.8 ± 0.9 c	10.1 ± 0.8 bc	12.7 ± 0.8 b	26 ± 1 a
Extractable K (mg kg^{-1})	178 ± 7 bc	162 ± 6 c	159 ± 4 c	170 ± 4 bc	188 ± 6 ab	203 ± 4 a
Bulk density (g cm^{-3})	1.36 ± 0.08 a	1.3 ± 0.1 a	1.3 ± 0.1 a	1.4 ± 0.1 a	1.38 ± 0.04 a	1.1 ± 0.1 b

Values are the mean of six replicate plots \pm standard error. For each soil property, values followed by the same letters are not significantly different (Tukey's test, $\alpha = 0.05$).

(summit, shoulder, and upper backslope) and areas of high soil accumulation (toeslope) (Figs. 3 and 4; other data not shown). Landscape positions characterized by moderate soil loss/accumulation (lower backslope and footslope) showed less variation in soil properties with depth, and concentrations of ammonium-N, total N, IC, OC, and EC did not significantly change with depth in the upper profile (0–40 cm) in these landscape positions (Figs. 3 and 4; other data not shown).

Soil properties measured in eroded landscape positions show the impact of subsoil exposure at the soil surface. Nutrient and OC contents are low in the surface soil and decline sharply with depth to very low values throughout the subsoil in the summit, shoulder, and upper backslope (Fig. 4; other data not shown). Soil IC contents are high throughout the profile in eroded landscape positions. Surface soil IC contents in the shoulder and upper backslope, which have the highest soil loss by combined tillage

and water erosion (Fig. 2), are as high as those in the C horizon (Fig. 4).

Deposition of non-mollic material over mollic material in the lower backslope was shown by determination of soil properties. Soil OC contents are highest in the 15–30 cm depth increment in the lower backslope; surface soil (0–15 cm) and soil at 30–45 cm depth have similar mean OC concentrations (Fig. 4). Conversely, soil IC contents decrease from the surface soil (0–15 cm) to the 15–30 cm depth increment, then increase at depths >30 cm (Fig. 4). In areas of net soil accumulation (footslope and toeslope), nutrient and OC contents and EC are higher, whereas IC contents are lower, throughout the top 60 cm of the soil profile compared to upper landscape positions (Fig. 4; other data not shown). Soil properties in the deepest depth increment (60–120 cm) are similar in all landscape positions (Fig. 4; other data not shown).

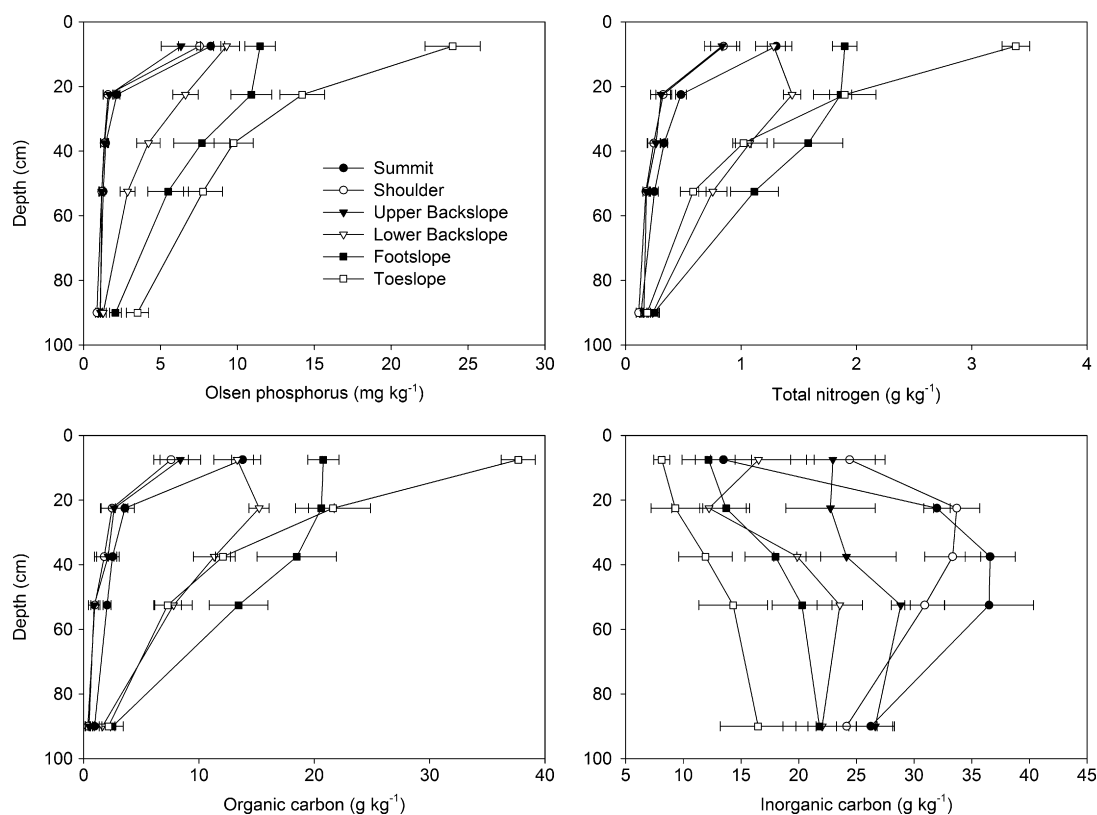


Fig. 4. Characteristics of soil cores (0–120 cm depth) collected near the center of each subplot prior to soil movement for soil-landscape rehabilitation. Soil properties were determined by horizon and converted to a depth basis in increments 0–15, 15–30, 30–45, 45–60, and 60–120 cm. Values are the mean of six replicate plots \pm standard error.

3.3. Post-rehabilitation soil properties

3.3.1. Surface soil properties

Because approximately 15–20 cm of soil were moved from lower to upper slope positions, the surface soil properties were subject to the greatest change in response to soil-landscape rehabilitation. Surface (0–15 cm) soil concentrations of nitrate-N, total N, P, and OC in the areas of soil addition (summit, shoulder, and upper backslope) were increased by a factor of two compared to concentrations measured before soil movement, while soil IC concentrations were reduced by approximately one-half (Table 3). Surface soil EC and K concentrations also showed a significant increase in areas of soil addition (Table 3). As expected, surface soil chemical properties in areas of soil addition were similar to those for the toeslope and footslope, from which the soil was taken (Tables 2 and 3). Gravimetric soil moisture measured during crop emergence was higher in upper slope positions of rehabilitated plots (areas of soil addition) compared to undisturbed plots (Table 3). Surface soil bulk density was not significantly different in rehabilitated and undisturbed plots in the summit and shoulder. However, bulk

density was reduced in the upper backslope in response to soil addition (Table 3).

Soil was neither added nor removed from the lower backslope, and surface soil properties showed no significant differences between rehabilitated and undisturbed plots, indicating that the plots remained uniform across the slope at each landscape position in these areas. Soil chemical properties in areas of soil removal were similar to those in undisturbed plots with the exception of phosphorus (Table 3). A high population of volunteer wheat was present in lower slope positions at the time of soil movement. Post-rehabilitation P contents may have been depleted in the rehabilitated plots by the removal of wheat biomass during soil movement. Soil bulk density in areas of soil removal (footslope and toeslope) was the same as in undisturbed plots (Table 3). Surface soil properties of undisturbed plots were generally unchanged at all landscape positions (Table 3).

3.3.2. Soil properties as a function of depth

Removal and addition of approximately 15–20 cm of soil, followed by tillage to 20–25 cm depth, influenced both surface and subsurface soil properties. The 15–30 cm depth increment was

Table 3

Relative change in surface soil (0–15 cm depth) properties in samples collected in undisturbed plots and rehabilitated plots approximately 6 months after soil movement

Soil property	Summit	Shoulder	Upper backslope	Lower backslope ^a	Footslope	Toeslope
Organic carbon						
Rehabilitated plots	2.4 ± 0.2 a	3.0 ± 0.1 a	3.1 ± 0.1 a	1.3 ± 0.1 a	1.1 ± 0.1 a	0.8 ± 0.1 a
Undisturbed plots	1.1 ± 0.0 b	1.2 ± 0.2 b	1.0 ± 0.4 b	1.0 ± 0.3 a	1.0 ± 0.1 a	0.9 ± 0.0 a
Inorganic carbon						
Rehabilitated plots	0.7 ± 0.1 b	0.5 ± 0.1 b	0.4 ± 0.1 a	0.8 ± 0.2 a	0.8 ± 0.3 a	0.9 ± 0.2 a
Undisturbed plots	1.1 ± 0.1 a	1.0 ± 0.1 a	1.0 ± 0.2 a	1.0 ± 0.4 a	1.0 ± 0.3 a	1.0 ± 0.0 a
pH						
Rehabilitated plots	0.994 ± 0.001 b	0.991 ± 0.001 a	1.001 ± 0.005 a	1.000 ± 0.005 a	1.008 ± 0.002 a	1.008 ± 0.002 a
Undisturbed plots	1.000 ± 0.000 a	0.999 ± 0.005 a	1.002 ± 0.005 a	1.004 ± 0.006 a	1.006 ± 0.001 a	1.009 ± 0.002 a
Electrical conductivity						
Rehabilitated plots	1.62 ± 0.05 a	1.45 ± 0.06 a	1.36 ± 0.03 a	1.02 ± 0.03 a	1.01 ± 0.05 a	0.86 ± 0.02 a
Undisturbed plots	1.10 ± 0.03 b	1.01 ± 0.03 b	0.98 ± 0.08 b	0.97 ± 0.05 a	1.01 ± 0.02 a	0.92 ± 0.03 a
Total N						
Rehabilitated plots	2.4 ± 0.2 a	2.7 ± 0.1 a	3.1 ± 0.1 a	1.2 ± 0.1 a	1.1 ± 0.1 a	0.82 ± 0.07 a
Undisturbed plots	1.11 ± 0.03 b	1.0 ± 0.1 b	1.0 ± 0.3 b	1.0 ± 0.2 a	1.0 ± 0.1 a	0.93 ± 0.04 a
Nitrate-N						
Rehabilitated plots	2.3 ± 0.2 a	1.5 ± 0.1 a	2.1 ± 0.0 a	1.11 ± 0.01 a	1.0 ± 0.2 a	1.2 ± 0.2 a
Undisturbed plots	1.2 ± 0.1 b	0.91 ± 0.06 b	0.79 ± 0.1 b	0.85 ± 0.1 a	1.2 ± 0.2 a	1.0 ± 0.1 a
Ammonium-N						
Rehabilitated plots	1.6 ± 0.1 a	1.4 ± 0.1 a	1.4 ± 0.3 a	1.7 ± 0.3 a	1.0 ± 0.2 a	1.0 ± 0.2 a
Undisturbed plots	1.7 ± 0.3 a	1.3 ± 0.4 a	1.3 ± 0.4 a	1.3 ± 0.6 a	1.1 ± 0.2 a	0.9 ± 0.1 a
Olsen P						
Rehabilitated plots	2.0 ± 0.4 a	2.1 ± 0.2 a	2.3 ± 0.1 a	1.4 ± 0.2 a	0.8 ± 0.0 b	0.5 ± 0.0 b
Undisturbed plots	1.0 ± 0.0 a	1.0 ± 0.1 b	1.2 ± 0.4 b	1.0 ± 0.2 a	1.1 ± 0.1 a	0.8 ± 0.0 a
Extractable K						
Rehabilitated plots	1.2 ± 0.0 a	1.5 ± 0.1 a	1.3 ± 0.1 a	1.1 ± 0.1 a	0.9 ± 0.1 a	0.7 ± 0.1 b
Undisturbed plots	1.0 ± 0.0 b	1.0 ± 0.0 b	1.0 ± 0.1 b	1.0 ± 0.0 a	1.2 ± 0.0 a	1.2 ± 0.1 a
Bulk density						
Rehabilitated plots	0.87 ± 0.03 a	0.92 ± 0.02 a	0.78 ± 0.03 b	0.89 ± 0.06 a	1.01 ± 0.07 a	1.08 ± 0.02 a
Undisturbed plots	0.91 ± 0.03 a	0.94 ± 0.03 a	0.98 ± 0.03 a	0.95 ± 0.05 a	0.91 ± 0.04 a	1.05 ± 0.1 a
Soil moisture (g g ⁻¹)						
Rehabilitated plots	0.26 ± 0.02 a	0.22 ± 0.00 a	0.25 ± 0.00 a	0.19 ± 0.02 a	0.25 ± 0.01 a	0.27 ± 0.02 a
Undisturbed plots	0.19 ± 0.01 b	0.18 ± 0.01 b	0.17 ± 0.01 b	0.17 ± 0.02 a	0.21 ± 0.01 b	0.28 ± 0.02 a
Soil strength (MPa)						
Rehabilitated plots	0.24 ± 0.06 a	0.27 ± 0.06 a	0.25 ± 0.06 a	0.37 ± 0.07 a	0.25 ± 0.04 a	0.28 ± 0.04 a
Undisturbed plots	0.22 ± 0.04 a	0.24 ± 0.05 a	0.24 ± 0.04 a	0.29 ± 0.06 a	0.23 ± 0.05 a	0.22 ± 0.04 a

Post-rehabilitation values are the mean of three replicate plots and are expressed as relative to the mean pre-rehabilitation value reported in Table 2 (post-rehabilitation/pre-rehabilitation). Soil moisture and soil strength were measured after soil movement only and are reported as measured values. Different letters indicate significant differences (Tukey's test, $\alpha = 0.05$) for rehabilitated vs. undisturbed plots within each landscape position.

^a Soil was neither removed nor added to the lower backslope in rehabilitated plots; values indicate consistency of soil properties with time.

directly affected by soil addition/removal and subsequent tillage. Soil concentrations of OC (Fig. 5A), nitrate-N, total N, P, and K in areas of soil addition were in most cases significantly higher than in undisturbed plots. There was a downward shift in OC (Fig. 5B) and other soil properties as a result of burial during soil movement. Nitrate-N was significantly higher in the shoulder and upper backslope of rehabilitated plots at all monitored depths compared to undisturbed plots as a result of the downward shift. Soil EC and concentrations of OC (Fig. 5), P, and total N were significantly higher in the summit and shoulder of rehabilitated plots in depth increments of 0–15, 15–30, and 30–45 cm compared to undisturbed plots. Grote and Al-Kaisi (2007) also report significant increases in soil OC concentrations to depths of 30–45 cm following addition of at least 15 cm of topsoil, but their plots were subject to 25 years of cropping that included annual deep tillage to 40 cm. In these experiments, the short-term change in soil chemical properties is due to the burial of soil by the addition of 15–20 cm of soil.

In the footslope, deposition of high-organic matter soil over the original A horizon (Table 1) resulted in soil nutrient and OC contents that did not significantly vary with depth throughout at least the top 40 cm of the profile prior to soil movement (Figs. 3 and 4). Removal of 15–20 cm of soil from the footslope did not result in a significant change in any measured soil property at any depth increment to 60 cm depth (Fig. 5; other data not shown). In the toeslope, nutrient and OC contents were high in the surface soil and declined appreciably with depth in the upper profile prior to

soil movement (Fig. 4). Removal of 15–20 cm of soil exposed soil lower in organic matter at the surface of rehabilitated plots. The net effect of soil removal was to shift soil in rehabilitated plots upwards 15–20 cm. Thus, as in areas of soil removal, soil properties in profiles of rehabilitated plots were similar to those in undisturbed profiles, but were offset by 15 cm (Fig. 5B; other data not shown). Soil movement resulted in a reduction in soil OC (Fig. 5A) and total N contents throughout the top 60 cm of the toeslope soil profile in rehabilitated plots, but no statistically significant change in other soil properties. The movement of soil from the toeslope and footslope to the summit, shoulder, and upper backslope resulted in surface soil properties in upper slope positions that were similar to those for lower slope positions (Fig. 6). The lower backslope experienced neither addition nor removal of soil, and soil properties were unchanged in this landscape position (Figs. 5 and 6; other data not shown).

Gravimetric soil moisture was not different in rehabilitated and undisturbed plots in any landscape position at depths >15 cm. Soil bulk density measured at 15–30-cm depth showed the same trends as for the surface soil: bulk density was significantly lower in the upper backslope of rehabilitated plots, but otherwise showed no differences. Soil strength was not significantly different in rehabilitated and undisturbed plots (Table 2). Soil strength was significantly greater in upper slope positions (summit, shoulder, and upper backslope) compared to lower slope positions (footslope and toeslope) in both rehabilitated and undisturbed plots at depths >20 cm. In all monitored landscape positions, soil strength increased with increasing depth. In the lower backslope, the resistance to penetration was high at depths ≤20 cm but at depths >20 cm, soil strength was relatively constant at values intermediate between those measured in upper and lower slope positions. Only in the shoulder and upper backslope at depths >35 cm did soil strength values exceed 2 MPa.

In most cases, soil properties in undisturbed plots showed no change at any landscape position at any depth between the fall (prior to soil-landscape rehabilitation) and the following spring (Table 3). The changes in soil properties observed following soil movement in rehabilitated plots are not expected to be due to over-winter changes. Simultaneous monitoring of soil properties in rehabilitated and undisturbed plots provides additional confirmation that observed changes in soil profiles are a result of soil movement within the landscape.

3.4. Soil productivity

Soybean yield in the first year after soil movement showed a strong response to changes in soil properties. Grain yields were significantly greater in the shoulder and upper backslope of rehabilitated plots compared to undisturbed plots (Fig. 7A). Overall yields in areas of soil addition (summit, shoulder, and upper backslope) were $2000 \pm 40 \text{ kg ha}^{-1}$, significantly ($\alpha < 0.05$) greater than yields in the same landscape positions of undisturbed plots ($1500 \pm 130 \text{ kg ha}^{-1}$). Conversely, soybean yields in areas of soil removal were significantly depressed compared to undisturbed plots (Fig. 7A). Yields in the areas of soil removal (footslope and toeslope) were $1670 \pm 150 \text{ kg ha}^{-1}$, significantly lower than yields in the same landscape positions of undisturbed plots ($3000 \pm 120 \text{ kg ha}^{-1}$). Similar spatial trends were observed in the second year after soil movement, but grain yields were more variable and the yield differential in the lower slope areas was lower than in the first year (Fig. 7B). Grain yields in the summit, shoulder, and upper backslope of undisturbed plots averaged $6700 \pm 980 \text{ kg ha}^{-1}$, compared to $9000 \pm 450 \text{ kg ha}^{-1}$ in areas of soil addition, but these differences were not statistically significant. Yields were significantly higher in lower slope areas (footslope and

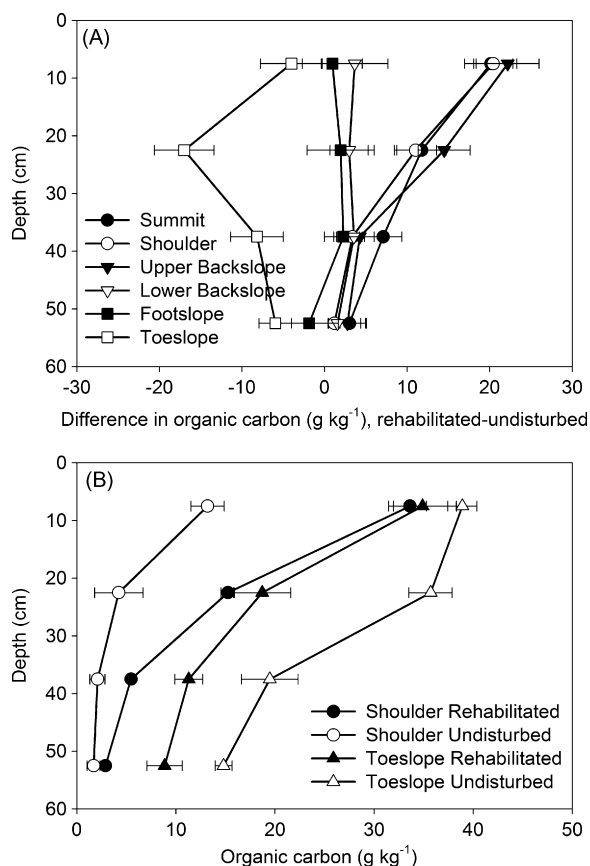


Fig. 5. Changes in soil organic carbon distribution after soil movement for soil-landscape rehabilitation. (A) Difference in organic carbon concentration in rehabilitated and undisturbed plots in each landscape position. (B) Organic carbon concentrations in the shoulder and toeslope of rehabilitated and undisturbed plots. Values are the mean of three replicate plots \pm standard error for depth increments 0–15, 15–30, 30–45, and 45–60 cm.

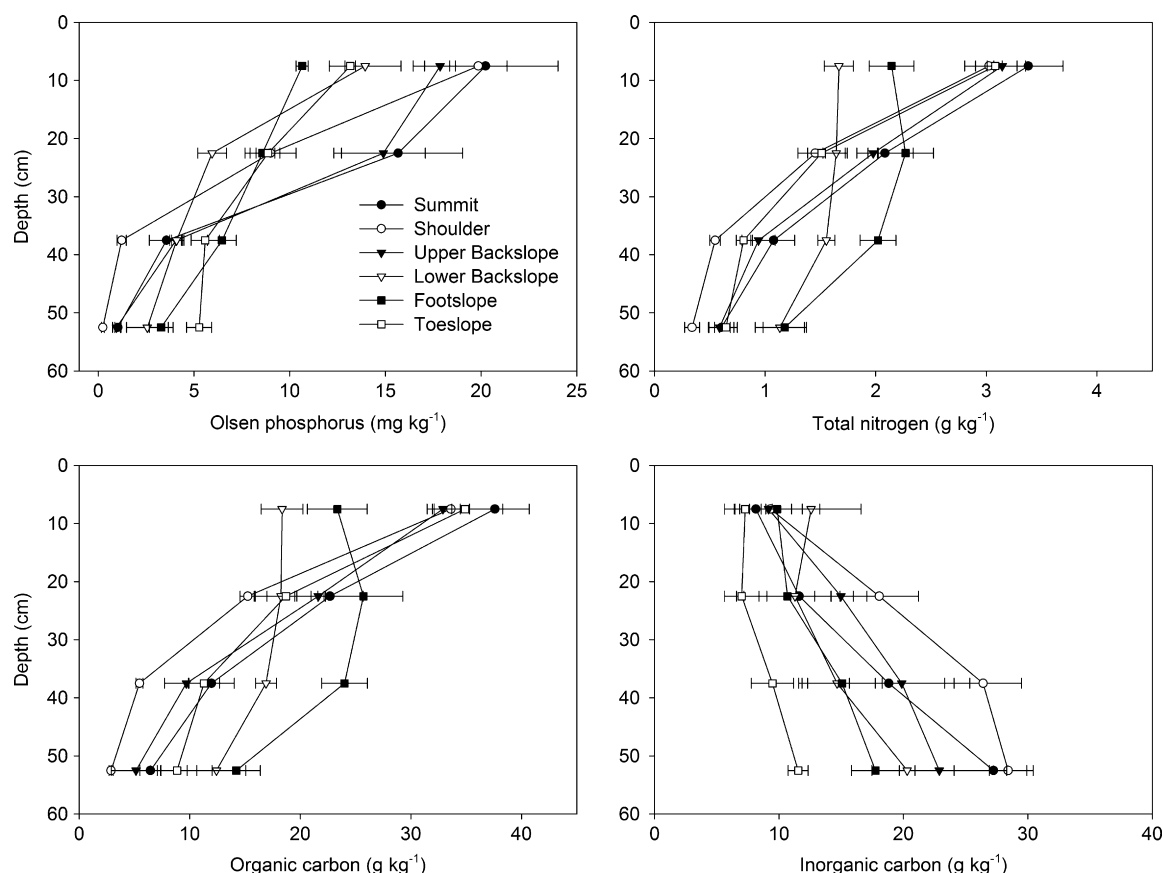


Fig. 6. Selected soil properties as a function of depth following soil movement for soil-landscape rehabilitation. Values are the mean of three replicate plots \pm standard error for depth increments 0–15, 15–30, 30–45, and 45–60 cm.

toeslope) of undisturbed plots ($12,400 \pm 240 \text{ kg ha}^{-1}$) compared to rehabilitated plots ($10,300 \pm 380 \text{ kg ha}^{-1}$). No soil movement occurred in the lower backslope, and there was no difference in grain yields in rehabilitated and undisturbed plots in this landscape position in either year (Fig. 7).

In rehabilitated plots, yields were relatively consistent from the summit through the footslope (year 1) and toeslope (year 2). In undisturbed plots, a large yield depression occurred in the area of largest soil loss by erosion, the shoulder and upper backslope (Fig. 7). The largest yield increase resulting from soil-landscape rehabilitation was observed in the upper backslope, where yields in rehabilitated plots were 63–65% greater than those in undisturbed plots, although this increase was only statistically significant in the first year (Fig. 7). Soil properties were much more uniform across landscape positions in rehabilitated plots (Fig. 6) than in undisturbed plots (Fig. 4), which likely contributed to the observed yield trends. These results indicate that addition of accumulated topsoil from lower slope positions to eroded upper slope positions can result in large yield increases in upper slope positions and more consistency in crop yields across the landscape.

The observed short-term yield increases in areas of soil addition were matched or exceeded by yield decreases in areas of soil removal (Fig. 7), so that grain yields across the study landform (summit through toeslope) were the same or lower in rehabilitated plots compared to undisturbed plots. Weather conditions in both the first and second season after soil movement were atypically dry. In 2006, the rainfall from soybean planting to harvest totaled 177 mm, 73 mm of which fell in September, after seed formation. The long-term average (from 1886 to 2007) for these dates is

331 mm. Average soybean yields (summit through toeslope) were $1820 \pm 100 \text{ kg ha}^{-1}$ in rehabilitated plots, significantly lower than in undisturbed plots, which yielded $2300 \pm 130 \text{ kg ha}^{-1}$; both treatments yielded less than the county average for the previous 10 years (1995–2005) of 2600 kg ha^{-1} (NASS, 2008). In 2007, rainfall from corn planting to harvest totaled 315 mm, 115 of which fell after September 1, whereas the long-term average for this period is 388 mm. Average corn yields were 9600 kg ha^{-1} in both rehabilitated and undisturbed plots, similar to the previous 10-year county average of 9200 kg ha^{-1} (NASS, 2008).

In normal and wet years, excessive soil moisture prohibits planting and other spring field operations in low-lying portions of the study area. Under typical conditions, lower slope areas, especially the toeslope, produce no grain or low grain yields. In these two dry years, the toeslope was the highest-yielding area monitored. Therefore, the yield depression observed in the toeslope had a large impact on overall yields, particularly in the first year after soil movement. Grain yields in the toeslope were not as severely reduced in the second year after soil movement. The results of this study suggest that the yield decrease was not attributable to a lack of soil macronutrients or compaction (Table 3). An expanded suite of soil properties is being investigated (including soil biological properties) to attempt to discern the cause for the yield depression in areas of soil removal. In this landform, a yield reduction in the typically low-yielding toeslope is not a major concern for the grower. In addition, the effect may be relatively short-lived, as was observed in the second year (Fig. 7B). Yield monitoring at this site will continue for another 2–3 years to evaluate soil productivity under a variety of crop and weather conditions.

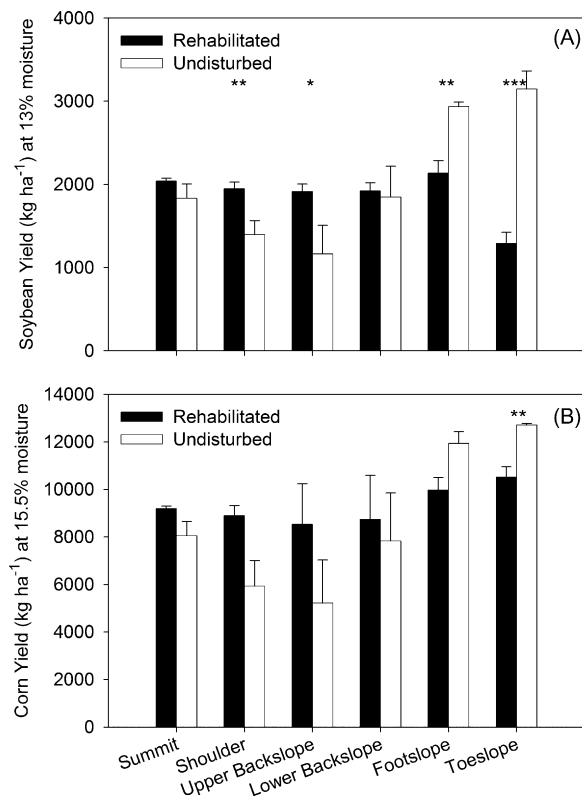


Fig. 7. Grain yield in the first (soybean, A) and second (corn, B) seasons after soil movement. *, **, and *** indicate significant differences in rehabilitated and undisturbed plots at the 0.05, 0.01, and 0.001 probability levels, respectively.

4. Conclusion

At this site, typical of cultivated landforms in the North American prairies, erosion has removed topsoil from upper slope positions and accumulated topsoil in lower slope positions. This experiment evaluated changes in soil properties and soil productivity as affected by movement of topsoil from areas of soil accumulation to areas of topsoil depletion. Soil-landscape rehabilitation was performed by moving 15–20 cm of soil from the lower slope (foothills and toeslope) to the upper slope (summit, shoulder, and upper backslope) positions. No soil movement occurred in undisturbed plots. As expected, this soil movement shifted soil properties upwards by 15–20 cm where soil was removed and shifted soil properties downwards by 15–20 cm where soil was applied. After soil movement, the surface soil in the upper slope of rehabilitated plots was similar to the lower slope, from which the soil was taken. Thus, soil properties were much more consistent from summit to toeslope in rehabilitated plots compared to undisturbed plots. Productivity was measured in two cropping years characterized by summer drought conditions. Undisturbed plots showed a typical decrease in yield in the shoulder and upper backslope (the most eroded soil positions). Yields were relatively consistent across landscape positions in rehabilitated plots. In rehabilitated plots, grain yields were increased by 30% in areas of soil addition, but decreased by 50% (year 1) and 20% (year 2) in areas of soil removal. These results indicate that movement of soil within a landscape from lower slope positions to eroded upper slope positions can result in large yield increases and more consistency in crop yields in upper slope positions, but additional research is needed to characterize the extent and longevity of the soil productivity impacts of soil removal and addition. These results indicate that soil-landscape

rehabilitation may be an alternative to managing gross landform-scale variability through variable rate technology and other precision agriculture approaches. These experiments will be continued to provide a more complete analysis of the economic costs and benefits of this approach.

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